Space Tethers and Space Elevators

Space Tethers and Space Elevators

Michel van Pelt

COPERNICUS BOOKS
An Imprint of Springer Science+Business Media

in Association with
Praxis Publishing, Ltd.

Published in the United States by Copernicus Books,
an imprint of Springer Science+Business Media.

Copernicus Books
Springer Science+Business Media
233 Spring Street
New York, NY 10013
www.springer.com

Library of Congress Control Number:
2009926314

Manufactured in the United States of America.
Printed on acid-free paper.

ISBN 978-0-387-76555-6 e-ISBN 978-0-387-76556-3

Contents

To Lucas and Thijs,
who may ride a space elevator one day.

Preface

Space tethers. Unlike space rockets and space probes, it is not a topic many people are familiar with. You may wonder what tethers have to do with space, or what they would be doing there. You may also wonder why it would be interesting to read a book about them.

On Earth, tethers, otherwise known as ropes or lines, are used primarily to bind things together and for climbing and pulling things up. Rock climbers and bungee jumpers use tethers, most elevators are based on them, and even people walking their dog can be considered users of terrestrial tether applications. In space, tethers have similar uses. For instance, they can be used to connect spacecraft to other satellites, space stations, or even asteroids. An advanced tether system, called a "space elevator," may even link Earth's surface directly to orbit, so you could climb all the way into space.

Space tethers also could be used to swing spacecraft from one orbit to another, or even from planet to planet, without using rocket propellant. Tarzan, the fictional jungle king of Edgar Rice Burroughs made famous in numerous movies, used a similar form of tether transportation, swinging from tree to tree on jungle liana vines. Although he is not a rocket scientist, Tarzan has to keep in mind various things that are also critical for designers of space tether systems. For instance, good judgment of the strength of tethers is vital; a breaking vine would seriously ruin Tarzan's day. Moreover, our jungle hero needs to select vines of the right length to reach the place he wants to go. With a too short liana, he will not get to his destination at all; if the vine is too long, he will land too low and maybe even hit the ground. Then there is always the danger of crashing headlong into a tree, so good planning of direction and speed is vital.

Tarzan swings and grabs one vine after another to get through the jungle. That means he needs to know when to let go in order to reach the next vine, and also make sure there is actually another good one to grab at the end of his trajectory—all in all, a fairly complex task, especially for someone educated by apes. Renting a jeep or a boat may be a better idea.

In space, however, tethers have many potential advantages. You can use them to get to the Moon and Mars or de-orbit spacecraft back to Earth without any rocket propulsion. You can drag them through Earth's magnetic field to generate an electrodynamic braking force, and at the same time produce electrical energy for the spacecraft. You can connect several spacecraft with tethers to accurately position them for formation flying. You can create artificial gravity inside a spacecraft by swinging it around at the end of a long tether. And think how much easier it would be to be able to put satellites on a space elevator and simply release them from the top floor, rather than launching them with expensive, noisy, non-reusable, propellant-gulping rockets.

Sounds like science fiction? As you read on, you may be amazed to learn about the number of actual space tether projects that have already flown. These range from small suborbital rocket experiments to large and complicated systems flown onboard the Space Shuttle. The first experiment flew as long ago as 1966, onboard the crewed Gemini 11 mission! Up until now, all tether space missions have been experimental, but in this book you will see what they may lead to. There is a wide array of ideas for small-scale as well as large-scale concepts that have the potential to revolutionize spaceflight in the coming decades.

This book first discusses the basic concepts regarding the use of space tethers, and the physics underlying their functioning. Next, we discuss where the ideas for space tethers came from and what missions with relatively simple tethers have already flown. The chapters after that describe more futuristic possibilities, using tethers to transport spacecraft from Earth into space, operate them in Earth orbit, and even make interplanetary missions more economical. Last, we discuss the main challenges that face the most exiting and potentially most useful applications of large space tethers.

Many thanks to Clive Horwood and John Mason of Praxis, who suggested that I write a book about this fascinating topic. John Mason's comments and inspiring suggestions were of great importance. Stella Tkatchova once again did an excellent job reading the text from a nonengineering perspective, and Alessandro Atzei helped tremendously by reading from an engineering point of view. My space-qualified friends Torsten Bieler, Peter Buist, Dennis Gerrits, Zeina Mounzer, Ron Noteborn, Rogier Schonenborg, and Arno Wielders provided ideas, useful comments and psychological support. Special thanks to the guys from Delta-Utec, Erik van der Heide and Michiel Kruijff, for up-to-date information on their YES missions and a critical look at what I wrote about tether deployment and dynamics. And last but certainly not least, thanks to my wife, Stefania, for all her support, comments, suggestions, and patience.

1

The Basics

The basic concept behind space tethers is not very complicated. Simply put, space tethers are long cables that connect spacecraft to other spacecraft or to objects such as spent rocket stages, asteroids, or even the planet Earth. When two things are connected by a tether, manipulating one object will influence the other; if we pull on one end of the cable, the spacecraft on the other end will also move. By connecting two spacecraft with a tether, we can force them to stay together and orbit Earth as one single system.

Even though objects in orbit are flying around in microgravity conditions, spacecraft in different orbits will turn around a planet or the Sun at different speeds. If we connect two such satellites with a tether, they will each try to go their own way and pull on the cable. The forces on such a tether in space can be very powerful; therefore, space tethers are usually made of thin strands of high-strength fibers. If electricity has to flow through them, conducting wires are also incorporated.

There are many types and applications of tether systems; as we will see, the possibilities for this novel technology are amazing. In this chapter the main types of space tethers are introduced, as a basis for the more detailed descriptions of concepts and missions in later chapters. However, as most tether applications have something to do with satellite orbits, we first need to understand how orbital mechanics work.

Orbits

Imagine throwing a ball horizontally. You will not be surprised by the fact that it follows a curved trajectory and hits the ground some distance away. You will also not be amazed that when you throw the ball a bit faster, it will land farther away. Because its initial horizontal speed is higher, while it is falling and accelerating toward Earth at the same rate as before, the ball will fly a longer distance before hitting the ground. Its trajectory is curved,

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_1,

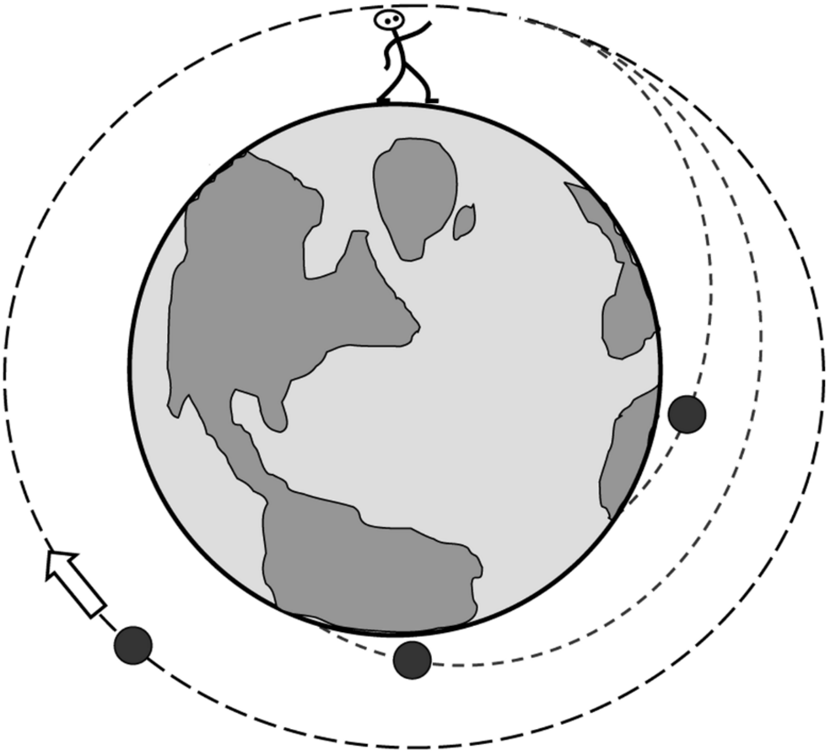

Figure 1.1: The faster an object, the further it travels before hitting the ground. At the right speed it will never hit the ground and thus enter an orbit around Earth.

because of the combination of its horizontal velocity and gravity pulling and thus accelerating the ball downward.

Imagine throwing, or rather shooting, the ball really fast. Now it goes very far, all the way over the horizon. Because Earth is round, its surface drops away under the ball. The result is that the ball will fly farther away than if we lived on a flat world. At a velocity of about 8 kilometer per second (5 miles per second), the curvature of the ball's trajectory under the pull of Earth's gravity is exactly the same as the curvature of Earth. In effect, the ball is continuously falling around the world, never hitting the ground (Fig. 1.1). It is in orbit, and will return to hit you in the back!

In reality you would not be in any danger, because Earth's atmosphere would slow the ball down so much that it would never reach you again. However, at an altitude of over 100 km (60 miles), there is hardly any atmosphere left to decelerate a moving object. In the vacuum of space the ball can circle Earth unhindered and become a satellite.

Now imagine you are standing on top of a tower 200 km (120 miles) high.

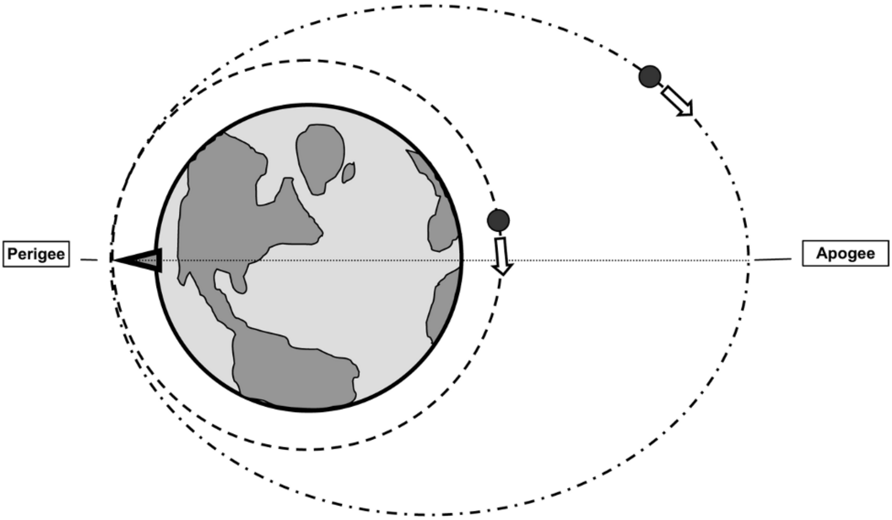

Figure 1.2: If a satellite is launched from a certain altitude with velocity higher than necessary for a circular orbit, it will enter an elliptical orbit.

If you shoot the ball at exactly the right speed, it will get into a circular orbit exactly 200 km above Earth's surface. What happens if you shoot it away at a higher velocity? Then the satellite has too much energy and flies too far to perfectly match the curvature of Earth. It will nevertheless still return to its point of origin (the top of the tower); instead of a perfect circle, the ball's orbit is now a large ellipse. In this elliptical orbit, the top of the tower is the point closest to the Earth. This is called the orbit's "perigee" (Fig. 1.2).

If you accidentally shoot the ball at a slightly too low velocity, the result would also be an elliptical orbit. However, now the trajectory is initially too curved to be a perfect circle, and the ball will drop down to an altitude of less than 200 km before returning to its point of origin. In this case the top of the tower is the orbit's furthest point from Earth, what is called the "apogee." If the velocity is much too low, the orbit intersects Earth's atmosphere. If that happens, the air drag will slow down the satellite even further and make it de-orbit.

Perigee and *apogee* are terms used for Earth orbits. The generic terms are *periapsis* and *apoapsis,* but the prefixes *peri*- and *ap*- or *apo*- are commonly applied to the Greek or Roman names of the planets being orbited: *perigee* and *apogee* for Earth, *perijove* and *apojove* for Jupiter, *periselene* and *aposelene* for the Moon, and *perihelion* and *aphelion* for satellites, planets, and other objects orbiting the sun.

Satellite orbits are normally changed with the help of rocket propulsion. Speeding up a satellite in a circular orbit by thrusting in the direction of its velocity will make it enter a larger, elliptical orbit; the perigee stays the same, but the extra speed increases the orbit's apogee. You can also make the satellite follow a smaller elliptical orbit by thrusting in the other direction, in effect putting the brakes on. Now the apogee stays what it was (the altitude of the original circular orbit), but the perigee is much closer to Earth.

Getting a satellite from a low circular orbit into a higher circular orbit normally involves two steps. First, the orbit's apogee is increased by accelerating the satellite with a rocket engine. The engine has to work only for a limited amount of time, until the right speed is achieved. Once the satellite has entered its new, elliptical orbit, it simply cruises unpowered over half an ellipse to its now higher apogee. This is called a Hohmann trajectory, and it is the most energy-efficient way for getting a satellite from a lower orbit to a higher one. Once it arrives there, the engine is ignited a second time. If the velocity is increased by exactly the right amount, the orbit becomes circular again. If the increase is too high, the satellite enters

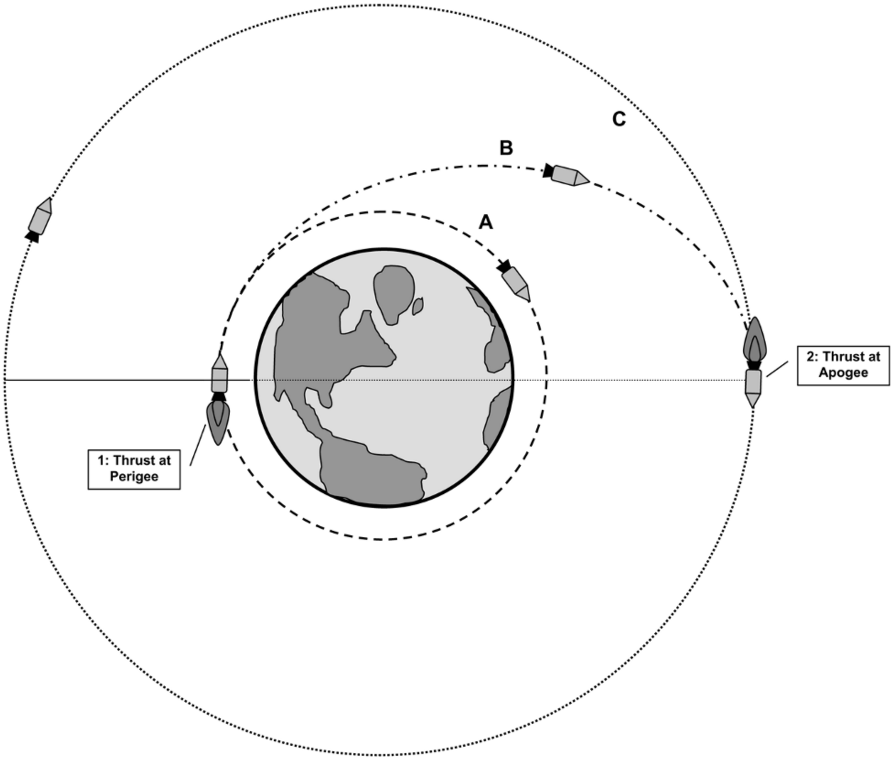

Figure 1.3: A thrust impulse in circular orbit A sends a rocket into the elliptical orbit B. A second thrust impulse half an orbit later (at the new apogee) will then send it into orbit C, which is also circular but much higher than orbit A.

another, larger elliptical orbit, with the previous apogee becoming the new perigee. After each kick from the rocket's engine, the old and the new orbit thus always have one point in common: the place where the rocket was ignited (Fig. 1.3).

Another important thing to know about orbits is that the higher the orbit, the lower the velocity required for a satellite to stay in that orbit. This sounds a bit contradictory, because didn't we need to speed up a satellite to move it from a low Earth orbit into a higher one? Yes, but the initial kick given to a spacecraft to increase its orbit's apogee only gives it a higher velocity at its initial altitude. As the satellite cruises along its new, elliptical orbit to a higher altitude, its velocity steadily decreases due to the gravity of Earth. Once it reaches its apogee, the spacecraft actually flies too slow to stay there; that's why it falls back to its perigee, which is at the same altitude as its original, pre-kick orbit (the common point of both orbits, where the rocket engine was originally fired). Falling down, it picks up speed due to the pull of gravity, and at its lowest altitude will move too fast to stay in a circular orbit there (in fact, at perigee it will move at the exact same speed it left with after the initial propulsive boost we gave it). It therefore moves back up to higher altitude again. If nothing else happens, the satellite will thus stay in this stable, elliptical orbit, constantly decreasing its speed on the way up, and increasing velocity on the way down (Fig. 1.4).

Now, at the elliptical orbit's apogee, we again need to give our satellite a little extra kick to increase its speed sufficiently to make it stay at that altitude, in a nice circular orbit. Nevertheless, its velocity in this stable, higher circular orbit will be lower than its orbital velocity in the original, lower circular orbit. The extra energy we gave it with the first kick has been spent on gaining altitude, not on a higher velocity at that altitude (remember, the satellite actually moves relatively slow at apogee).

If the force of Earth's gravity would be the same at any altitude, we would expect to require a higher horizontal velocity for higher orbits; a higher orbit means a bigger circle around Earth, which means a less curved trajectory, which in turn means a higher horizontal velocity. It would be similar to the example of throwing a ball: the higher the horizontal speed, the less curved the trajectory and the wider the orbit, and thus the farther away the ball flies.

However, a planet's gravity is not constant at all, but instead weakens with distance. The farther away (in effect the higher the altitude), the lower the strength of Earth's gravity. If you weigh 70 kilograms (kg) (150 pounds) at Earth's surface, you will weigh 41 kg (90 pounds) at an altitude of 2000 km, and only 2 kg (4 pounds) at 36,000 km (22,000 miles) above Earth. The higher the orbit, the weaker the pull of gravity, and as a result the lower the velocity required for a ball or satellite to stay in orbit and not fall back down

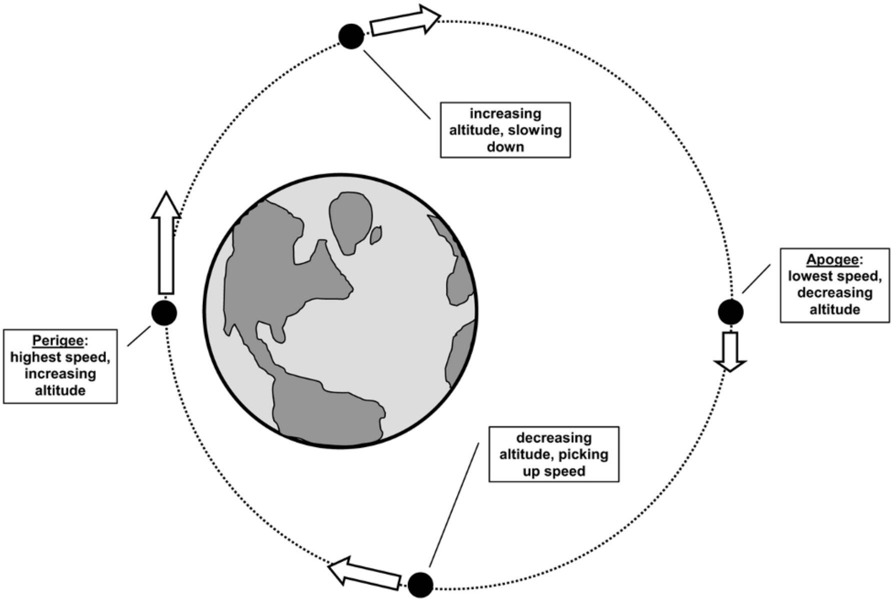

Figure 1.4: A satellite has its highest velocity at perigee and its lowest velocity at apogee.

to Earth. In other words, because its rate of fall toward the planet is less due to the lower gravity, a satellite's horizontal velocity can be lower while its trajectory will still be sufficiently curved to avoid hitting the ground. The effect of gravity decreasing with altitude wins over the earlier explained effect of requiring a higher orbital velocity for a larger orbit. The net result is thus that the higher the orbit, the slower the satellite.

To stay in a circular orbit at an altitude of 150 km (90 miles) requires an object to move at a velocity of 7.8 km per second (4.8 miles per second). At an altitude of 2000 km (1200 miles), this has decreased to 6.9 km per second (4.3 miles per second), and at 36,000 km (22,000 miles) the orbital velocity is only 3.1 km per second (1.9 miles per second). This velocity in combination with the size of the orbit means that at an altitude of 36,000 km (22,000 miles), a satellite will make one complete orbit in exactly 24 hours. Because Earth also rotates once in 24 hours, a satellite at that altitude and orbiting above the equator will appear to hang over the same spot on Earth continuously. This is called the geostationary Earth orbit. If a spacecraft orbits at the same altitude but not exactly above the equator, it will seem to remain motionless above the same longitude but periodically move north and south. Such orbits are called geosynchronous orbits (GEOs); a geostationary orbit is thus a special type of GEO. Even farther out, the Moon orbits at an altitude of about 384,000 km (240,000 miles) and a

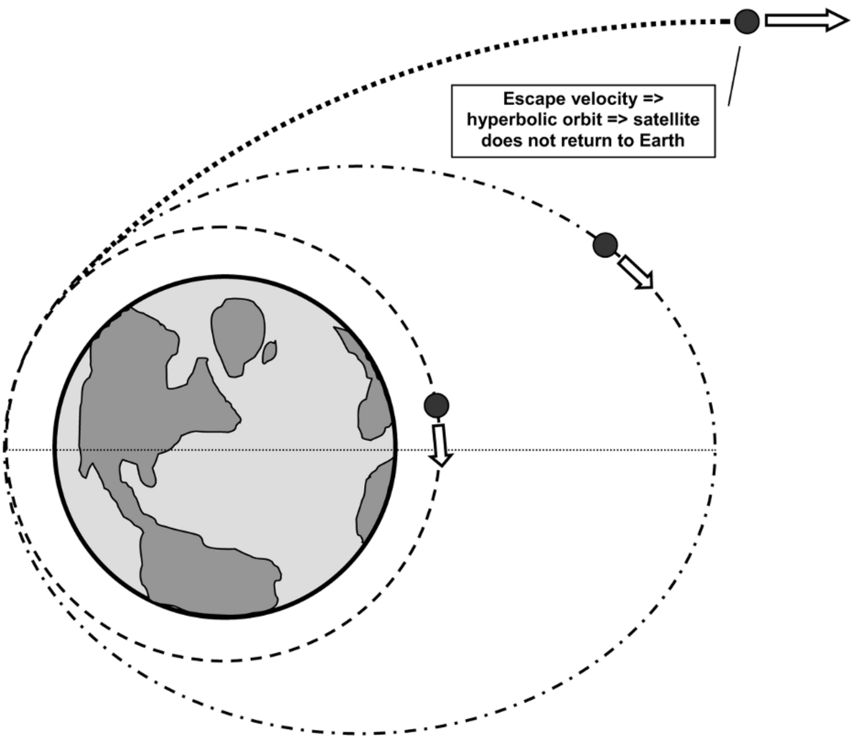

Figure 1.5: A satellite that achieves a speed equal to or greater than Earth's escape velocity does not return to Earth but enters a new orbit around the Sun.

velocity of only 1 km per second (0.6 miles per second). Because of its low speed and its very large orbit, it takes the Moon over 27 days to circle around Earth once.

Since the strength of gravity diminishes with altitude (called the gravity gradient), and we can get to a higher altitude by increasing orbital velocity (increasing the orbit's apoapsis), there must be a speed that makes a satellite fly so far away from a planet that it no longer returns. This is called the escape velocity. Below the escape velocity a satellite will follow a circular or elliptical, and thus closed, orbit. Above this speed limit the orbit is an open hyperbola and the spacecraft will "escape" the gravitational influence of the planet (Fig. 1.5).

For Earth, the escape velocity from the surface is about 11 km/s (7 miles/s). Because gravity weakens with altitude, the escape velocity, for example, at an altitude of 5000 km (3100 miles) in space is less: 8.4 km/s (5.2 miles/s). To fly a spacecraft to other planets, it needs to go faster than the local escape velocity. Away from Earth, the gravitational influence of the Sun will become dominant, and the spacecraft will enter an orbit around the Sun. In such an orbit it may fly from one planet to another. For example, with the right increase in velocity a solar orbit that starts in the vicinity of Earth (the perihelion) can reach all the way to the orbit of Mars (the orbit's aphelion). Using such an Earth–Mars Hohmann trajectory, we can efficiently send an interplanetary spacecraft to the red planet. However, we will have to boost the satellite out of Earth orbit at exactly the right time, so that when it arrives in the orbit of Mars that planet will actually be there, at the same location.

Of course, the Sun has its own escape velocity. When this is exceeded, a spacecraft leaves the solar system and enters interstellar space. It will still be in orbit around a dominant center of gravity, though—the heart of the Milky Way, our own galaxy.

Changing orbits by thrusting with rocket engines is expensive in terms of mass. For instance, bringing a 1500-kg (3300-pound) satellite from a low, 150-km (90-mile) altitude orbit to GEO with the efficient method described before takes about 4000 kg (8800 pounds) of propellant (using a typical spacecraft propulsion system burning monomethyl hydrazine and nitrogen tetroxide). This means that the total mass the launcher has to initially put in low Earth orbit is about 3.7 times the mass of the actual GEO satellite! Moreover, the propellant required for the transfer needs to be packaged into tanks that have a considerable mass as well, and also the mass of the essential pipes, filters, valves, structures, and rocket thrusters diminish the "useful" satellite mass delivered in GEO.

The GEO is a popular location, because seen from Earth a satellite in this orbit appears to hang more or less stationary in the sky (it will move north and south a bit, if not orbiting precisely above the equator). Such a satellite can thus be used to permanently observe the same half of Earth, or act as a giant radio/television tower. With three satellites, we can in principle cover the whole planet (with two satellites we would not be able to properly monitor the edges of the half globe observed by each spacecraft; some overlap is needed). Many weather and communications satellites are therefore placed in GEO. There are now about 350 active satellites in that orbit (theoretically three giant satellites would be enough, but those would be impossible to launch, and furthermore there are many different types of satellites and applications, operated by many different countries, organizations and companies) (Fig. 1.6).

If we would somehow be able to transfer a satellite from a low orbit into GEO without rocket propulsion, we would save a large amount of mass on propellant and onboard propulsion equipment. This would then enable us to use a smaller and therefore cheaper launcher. Launching a 1500-kg (3300-pound) spacecraft into a low orbit can be done, for example, with a Russian

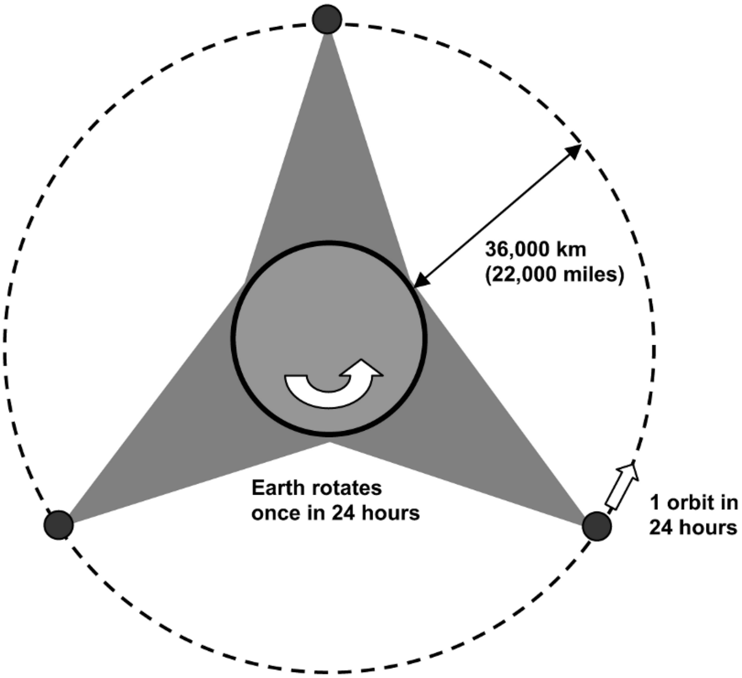

Figure 1.6: With three satellites in a geosynchronous orbit (GEO), practically the entire globe can be covered.

Eurockot launcher, which costs about $15 million. To launch the same satellite plus the added mass for propellant and equipment needed for the transfer to GEO takes something like a Russian Soyuz rocket, with a launch price of some $45 million—three times the price of the smaller rocket. As we will see later on, the smart use of space tethers (using so-called tether propulsion systems) makes it possible to transfer satellites into the desired orbit with no or relatively little amounts of propellant, potentially resulting in important launch cost savings.

Formation Flying

Probably the most obvious application of tethers is to use them to connect satellites and thus keep them together. In orbit, spacecraft that are initially close together tend to slowly drift away from each other. This may be because they were put in orbit with slightly different initial velocities, or because they are orbiting at somewhat different altitudes. Moreover, Earth is not perfectly round, and as a result its gravity field is not exactly the same everywhere at a given altitude. Satellites at different locations thus experience slightly different disturbances in the gravity field and eventually start to move in different directions.

Propulsion with small rocket thrusters can be used to push back satellites that drift away from their positions, but that requires propellant. Eventually the propellant runs out and then there will be no way to keep the spacecraft under control. Moreover, to keep track of the spacecraft's position with respect to other spacecraft, we will need to equip each satellite with accurate position measurement sensors. The necessary propulsion and sensor equipment adds complexity and risk, and increases the mass and cost of the satellites. In addition, there are formation-flying applications for which even the smallest amount of thrust can be too disturbing.

Using tethers, we can build up a constellation of physically interconnected satellites that act as a single, much larger spacecraft, without the need for propulsion and complicated sensors to keep the cluster together. For example, a large radio astronomy antenna dish, requiring a very large spacecraft, could be replaced by a series of smaller antennas on smaller spacecraft. For these small antennas to work together and function as a single large dish, they have to remain very accurately positioned with respect to each other. The simplest method to keep them together is to connect them with cables and thus force them to stay in a tight formation, like flies caught in a spider's web.

However, since the cables need to be long and yet light, because otherwise it becomes too expensive to launch them and too difficult to roll them up to fit in the launcher, they will need to be very flexible. That means we can pull on the tethers, but the moment we push them the cables will go slack and we lose control of our herd of spacecraft. In other words, tethers can be used to prevent satellites from flying away, but we need something else to keep them from moving toward each other. Rocket thrusters can be used for that, but they would have to work continuously and thus use up a lot of propellant, which is what we tried to avoid by using tethers in the first place.

A better idea is to make the constellation spin around its own center of mass. This results in a centrifugal force that tries to make the satellites fly outward, and in reaction a centripetal, pulling force on the tethers (physics purists say that the centripetal force is only an apparent force, not a real force, but we can ignore the mathematical niceties here). The pull will keep the tethers taut, ensuring that the satellites all stay together. Imagine spinning around fast while in each hand holding a rope with a weight attached. As an interconnected constellation, the three of you will keep your relative positions with respect to each other. The "push" that prevents the weights from crashing into you is provided by the centrifugal forces caused

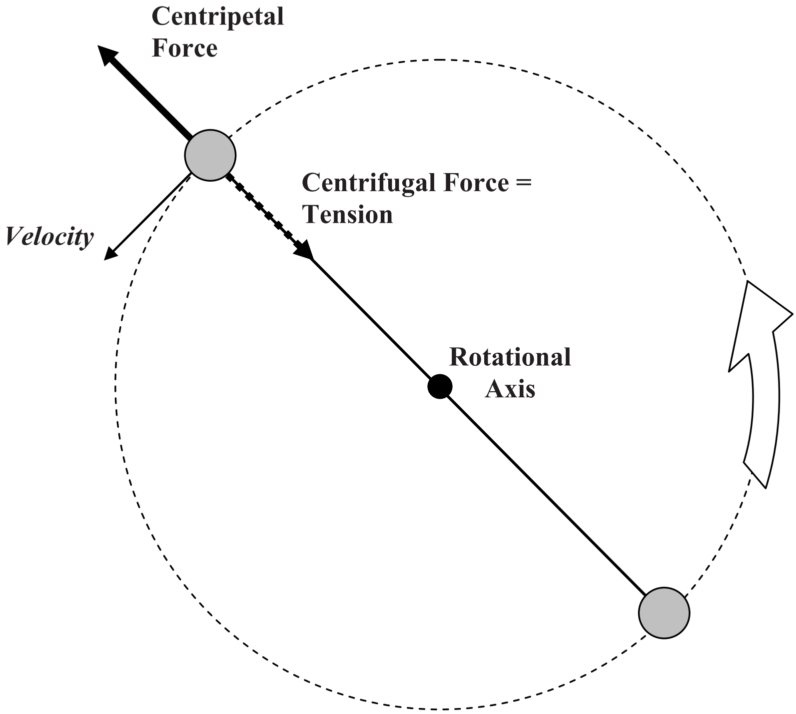

Figure 1.7: Centrifugal and centripetal forces in a rotating constellation with two masses or satellites.

by the rapid rotation, while the taut ropes prevent them from shooting away due to equal but inward directed centripetal tension forces (Fig. 1.7).

The downside of this method is that the group of satellites needs to rotate; their relative positions may remain fixed, but to the rest of the universe the satellites are constantly moving. This is not practical for many formation-flying applications, such as observing a planet or a star. There are, however, other ways to push spacecraft away from each other that do not use propellant and that can be combined with tether interconnections. This will be explained later (see Let's Stay Together, in Chapter 5).

Safety Tethers

If tethers can be employed to keep satellites together, it is not a far stretch to imagine their use in securing astronauts to prevent them from drifting away. In the 1960s the first spacewalkers used tethers that not only secured them to

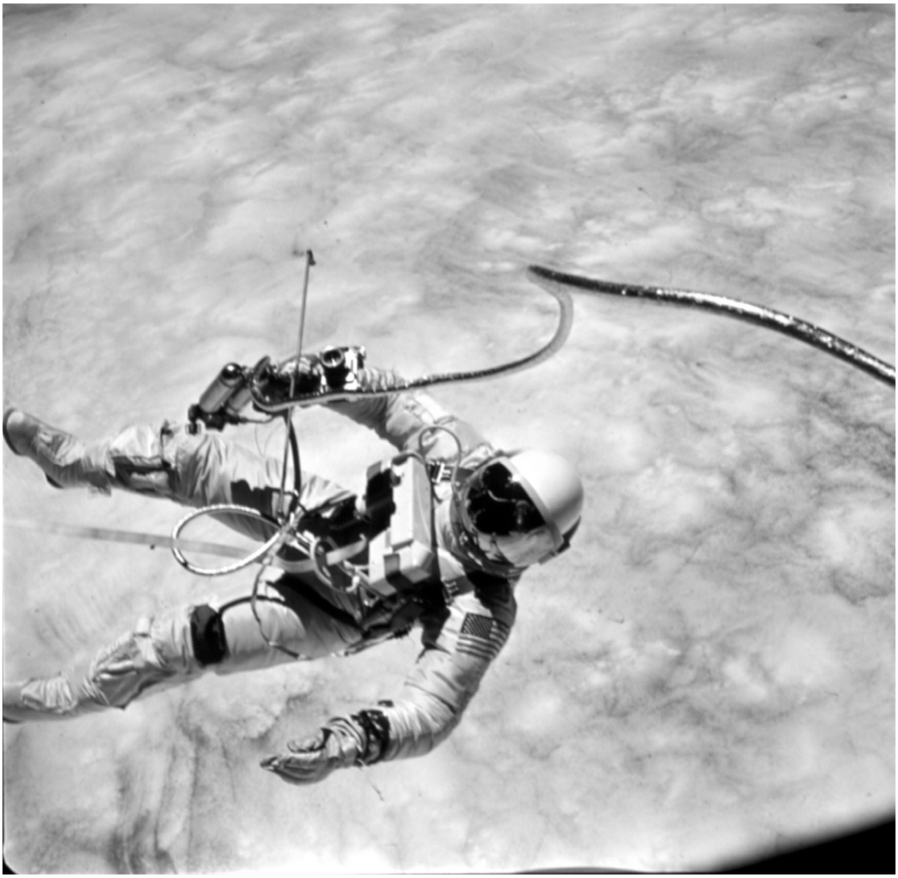

Figure 1.8: Astronaut Ed White during his space walk in 1965. He was connected to the Gemini 4 spacecraft by a long tether. (Courtesy of the National Aeronautics and Space Administration [NASA].)

their spacecraft but also contained wires and hoses for electrical, communication, and life support systems. At the end of a spacewalk, astronauts pulled themselves along the tether back to their capsules. Nowadays, spacesuits have their own, completely independent systems included in an attached backpack, but cables are still used as safety lines that connect astronauts to their spacecraft or space station (Fig. 1.8).

The tethers used for this function are relatively short, on the order of several meters. However, researchers at the Massachusetts Institute of Technology (MIT; Cambridge, MA) have devised an application with long tethers that can help astronauts strolling across the surface of small asteroids without floating away. Asteroids have very little gravity, so walking on them is much more difficult than walking on a planet. An asteroid with a diameter of less than 8 km (5 miles) would have so little mass and therefore gravity that an astronaut could easily fly off into space when making a small jump or even a step.

Tying a lightweight rope all the way around an asteroid could be a solution; astronauts could attach themselves to this safety line and maneuver or even walk along the surface. The MIT researchers envision that their system will be deployed by an astronaut or spacecraft unwinding a spool of rope while flying around the asteroid. The rope might cut into the soft, granular surface of an asteroid, but even then it could at least give spacewalkers something to hold onto.

Artificial Gravity

Microgravity, or weightlessness, exists inside an orbiting spacecraft because its contents (including any astronauts) are falling around Earth—we call this "free fall"—at the same speed as the spacecraft itself (and not, as is often believed, because there is no gravity in space). It is like being inside a falling elevator, but without the hard landing at the end. Astronauts inside the International Space Station (ISS) can simply float through its many modules, have dinner on a wall, and sleep on the ceiling. Because of the microgravity, there is no gravity-defined up or down.

This is fun for the astronauts, but the main use for space stations is that the microgravity conditions allow many kinds of experiments that are not possible on Earth. It is like turning off gravity. Fluids that float one on top of another on Earth can suddenly be mixed, as there is no gravity-induced separation based on differences in density. Larger and purer crystals can be grown, and the importance of gravity for the growth of cells and microbes can be studied.

We can even do combustion experiments that are not possible on the ground. A candle burning in space does not show the familiar elongated shape of the flame, but instead is spherical and almost transparent blue. The spherical shape is caused by the lack of convection, that is, heated air moving up, because that depends on gravity. There is no "up" for the hot air to go to, so it just stays hanging around the flame. The combustion in the hot bubble is very efficient because partly burned particles are not rapidly transported away by rising hot gases, but instead remain near the heat so they can burn up completely. Microgravity allows us to study combustion processes in great detail, which teaches us how to optimize combustion, for example, in car engines on Earth, and thereby reduce pollution.

However, if we want to fly people to Mars, microgravity is not so great.

Astronauts' bodies get upset by the lack of gravity. Blood normally pulled down into the legs now tends to move upward to the head, muscles are used much less and therefore deteriorate, and the body notices it do not need to maintain a strong skeleton anymore so it allows bones to weaken (leading to a loss of bone mass). Even though astronauts onboard the ISS typically exercise 2 hours a day to mitigate muscle atrophy, their strength inevitably weakens, especially in the legs. After half a year on the station, it may take an astronaut months to gain back his normal strength. As a result, healthy space explorers who land on Mars after a flight of half a year may not even be able to walk anymore, despite the much lower gravity on the red planet.

The centrifugal force that can be used to keep tethered satellite clusters together can also be employed to generate artificial gravity. Fill a bucket with water and swirl it around at the end of a length of rope. If you do it fast enough, the water will not spill out. It is as if the liquid is pulled toward the now vertical bottom of the bucket. Another analogy is riding through a loop in a roller coaster without falling out. Even while upside down you are being pushed into your seat by the artificial gravity generated by the train's velocity in combination with the curved track.

In a similar way, putting crewed modules at the end of long beams and having the spacecraft rotate can generate artificial gravity for astronauts. That enables them to live more normally and prevents them from being affected by the harmful physiological changes resulting from exposure to microgravity. In principle, we can attach such modules to each other with heavy structures and thus create a spinning wheel, with people living on the inner rim. This is the idea behind classical designs for wheel-shaped space stations such as seen in the movie *2001: A Space Odyssey* and in many conceptual studies for space colonies (Fig. 1.9).

The level of artificial gravity in such a system is determined by the length of the beams between the modules, the spacecraft center of rotation (i.e., the center of mass), and the rotational speed. The gravity level can be raised by lengthening the beams as well as by increasing the rotational speed. We can easily check this out with the earlier described bucket of water on a rope. The artificial gravity increases linearly with the length of the beam/rope and with the square of the number of rotations per minute. Thus, a double beam length (i.e., radius) gives a doubling of the "gravity" level if the number of rotations per minute is kept the same, but doubling the rotational speed increases it by four.

In theory, a gravity similar to that on Earth can be achieved with a spacecraft with short beams that rotates very fast, for example using a radius of 4 meters (13 feet) and 15 rotations per minute. However, if you have ever sat on a fast merry-go-round and moved your head, you know that fast